BIOMECHANICAL KNEE JOINT FOR EXOSKELETON

SCOPE OF WORK

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ABSTRACT

For our Senior Design Project, we were tasked by the LLEAP club (part of EMPOWER) to design and manufacture a biomechanically accurate, actuated knee joint to be integrated into their exoskeleton. In the following Scope of Work, we have outlined relevant background information on the knee joint (both in humans and exoskeletons), further detailed the sponsors and users needs, and outlined the scope of our project (including a general timeline in the form of a Gantt chart and objectives).

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1. INTRODUCTION

We are a team of mechanical and biomedical engineering seniors at California Polytechnic State University, San Luis Obispo (Cal Poly). The project outlined in this scope of work is to design a multi-degree of freedom knee joint that follows the natural joint motion of a human knee. The joint will be put onto an exoskeleton, so it must withstand the entire weight of the user and remain as lightweight and small as possible to allow for mobility. The knee joint will be built for the Lower Limb Exoskeleton Assist Project (LLEAP) club at Cal Poly and will be integrated into the 2023 prototype. The project is funded by the TECHE lab and the project sponsor is Professor Eric Espinoza-Wade, who has an expertise in dynamic systems analysis and control systems engineering for health science.

The goal of this report is to define the scope of work for the project and propose a plan for completing the design challenge within the school year. In this report, we will detail background research we have completed on the customer needs, similar products, and technical challenges for our project. We will define the needs and wants of the interested parties and the extent of our design challenge in the Project Scope. We will state what measurable specifications we plan to achieve and how our product will build on and outperform similar, existing knee joints in the Objectives section. Finally, we will discuss how we plan to meet all of these goals in a timely manner in the Project Management section before restating important takeaways in the Conclusion.

2. BACKGROUND

2.1. STAKEHOLDERS AND NEEDS

In order to complete this project, we needed to understand the needs of the user and familiarize ourselves with knee biomechanics. This was completed by researching peer reviewed articles and journals through Google Scholar and PubMed.

Provided below is a labeled diagram of the knee joint, Figure 1, to provide a base layer of information necessary to understand the analysis of the joint. For terminology, know that "medial" refers to inner and "lateral" refers to outer. The knee joint consists of the femur (upper, thigh bone), tibia (lower, shin bone), the patella (knee cap), fibula (lateral bone to tibia), a series of ligaments that hold the joint together (ACL, PCL, MCL, LCL), and cartilage acting as shock absorbers.

The knee rotates between the Femoral Condyles (covered in Articular Cartilage) and the Meniscus (cartilage shock absorber), which lie between and attach to the femur and tibia, respectively.

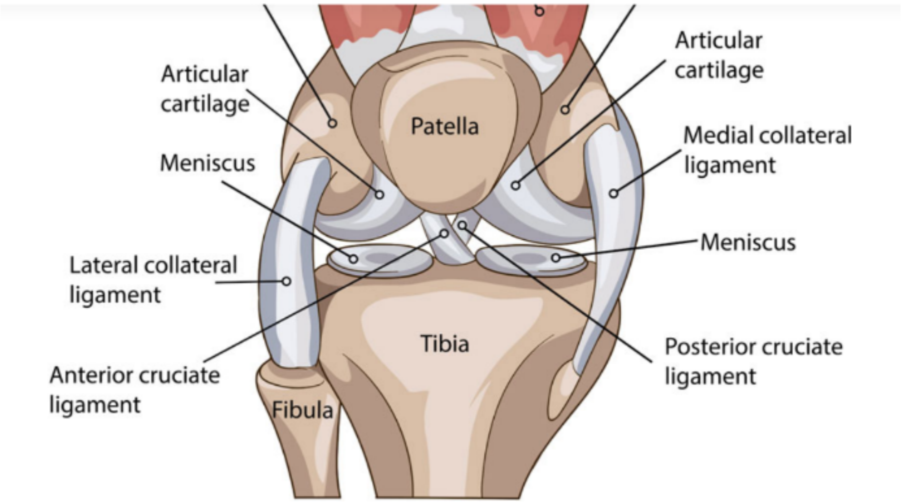

Figure 1. Anatomy of the knee joint [1].

Rotation of the knee joint does not occur around a singular axis; rather, as the joint rotates, the point of rotation moves as well. While this movement of the point of rotation has many approximations for a singular axis [2], the path of rotation is not defined for general knee anatomy because of its complexity and specificity to individuals. For more information, see table 3 in Appendix A.

Although many current lower limb exoskeletons utilize designs with single points of rotation, simplifying human biomechanics in such a manner can cause misalignment and "undesired interaction forces" [25]. Because there is a gradual buildup of force or torque during the gait phase, there is a sudden drop during maximum flexion, which causes misalignment in fixed rotational designs. One degree of freedom is enough to cause joint misalignment. Therefore, when the anatomical and knee joint kinematics are mismatched, unwanted forces and torques in the musculoskeletal system result.

A study assessing effects of exoskeleton misalignment on knee joint load showed significant knee misalignment with the use of a lower limb treadmill exoskeleton, especially on the thigh interaction forces. These misalignment interaction forces increase with the inertia of the exoskeleton [26]. When the femur slides over the tibia during the walking gait, the knee is displaced from its center position, which is shown in Figure 2. This cannot be accounted for in one degree of freedom exoskeleton systems [27].

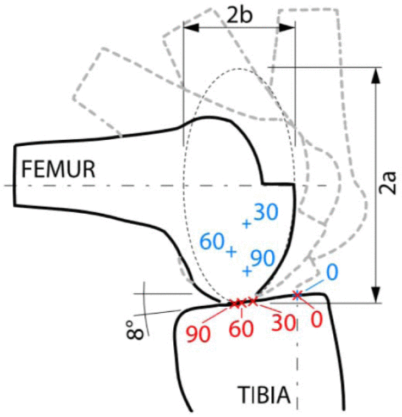

Figure 2. Displacement of the center of the knee [26].

In addition to joint misalignment, having an exoskeleton that does not mimic joint rotation results in wasted power transmission [28]. The human-device interface dynamics cause shear forces, joint misalignment, and compression at the interfaces, which results in 50% of mechanical power being lost in transmission to the body [29]. Although this study found this value, no other resources on power transmission were found. Because of this, while a definite conclusion on the amount of power loss cannot be defined, the potential for wasted power due to misalignment certainly exists.

Both rotational misalignment and issues with power expenditure affect exoskeleton users. As exoskeletons become more accessible to the general population and used by more individuals for longer durations of time, undesired interaction forces at the knee will cause more damage to the musculoskeletal system in exoskeleton users.

While there are many approximations for the rotational axis of the knee, the research found was inconclusive in identifying an exact rotational point. As knee joint anatomy varies based on the user, data on our potential user's anatomy must be collected and accounted for in the part geometry. A description of all stakeholders and needs references is found in Table 4 in Appendix A.

2.2. EXISTING DESIGNS

In the prosthetic knee industry, multi-axial robotic prosthetics have begun to be developed in order to improve bionic performance, net energy expenditure, and prosthetic stability [30]. The four-bar linkage mechanism is widely used in the knee prosthetics industry for this exact reason. The femur and tibia bone shape is commonly modeled in the linkages with a stretchable nylon cord that can be adjusted according to the user. Information was gathered by looking at existing four-bar linkage designs, specifically analyzing knee prosthetics in research articles and patents.

Awad et al [30] created a semi-active prosthetic knee to increase the accuracy of knee prosthetic rotation, which is shown in figure 3. One of the four-bar linkages is replaced with a motor and ball screw system which, when actuated, changes the angle of the linkage. This adjusts the path of the system and moves the joint.

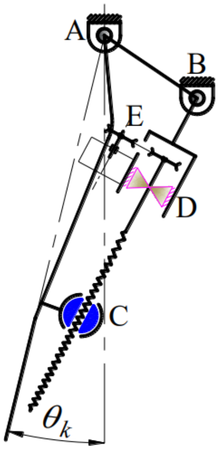

Figure 3. Four-bar linkage with motor screw system [30].

Figure 4 shows an additional existing design for a multi-axial prosthetic knee made for alpine skiing [32]. A four-bar linkage system, a pneumatic shock absorber, and coil spring were used by the prototype. This prototype was created for an above-knee amputation, which is different from our project in terms of joint kinematics, but provides an interesting design.

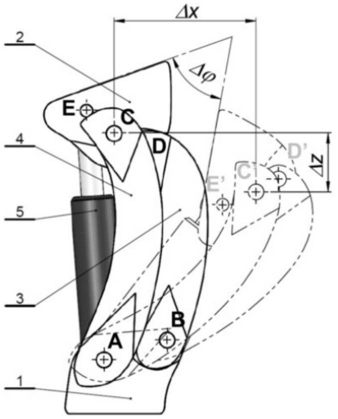

Figure 4. Additional existing design for a multi-axial prosthetic knee [32].

We researched current knee exoskeleton products by researching patents. These patents had designs that ranged from four-bar linkages to series spring actuators. Each design was unique and introduced new ideas for our design and consideration while generating ideas. A summary of the patents we researched is in Table 4 in Appendix A.

We found many different four-bar linkage designs that all had a unique way of creating a compact, robust linkage design to mimic the motion of a real human joint. One great patent is "Steady ratio four-bar linkage for genuflective energy harvesting" which discusses the design of a four-bar linkage, shown in Figure 5, which mimics the human knee's range of motion [16]. The patent discusses the details of the design, explaining what each link does and includes the dimensions of each link.

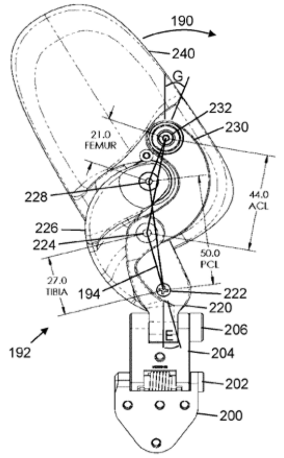

FIG. 15

Figure 5. Detailed design of four-bar linkage which mimics the human knee [16].

2.3. TECHNICAL RESEARCH

Another useful source of information came from reading technical articles. One of the most useful articles discusses a variety of materials, manufacturing, and actuation methods used in existing exoskeletons [19]. A second source discusses the benefits of integrating compliance, or flexibility, into an exoskeleton [20]. Traditional exoskeletons are very rigid, with a rigid drivetrain as well. Incorporating compliance is very beneficial for biomechanics and for user comfort. A third source discusses the impact on control methods and tertiary assistance from the ankle joint in the ability of a user to self-select their walking pace and walk as fast as possible [21].

Another source discusses the nuances of spinal cord injury and the other complications that can come with loss of function of limbs, torso, etc [22]. Keeping these things in mind will help us design a biomechanically accurate joint which will not injure the user or contribute to any secondary symptoms. In another source, the authors examine the nuances of the human gait and determined the effectiveness of exoskeletons in improving symmetric walking [23]. This article provides a lot of insight into assisting with a natural gait. The final article focuses on the importance of customizing exoskeletons to each user [24]. Every part of the human body varies in size and proportion, so being able to accurately customize parts of an exoskeleton is very beneficial for maximizing biomechanical accuracy. A summary of all technical journals found during our research can be found in Table 5 in Appendix A.

3. PROJECT SCOPE

Our goal is to design and fabricate a biomechanically accurate knee joint to be used by the exoskeleton being created in LLEAP for a user that is unable to walk on their own. The knee joint must match the translation and rotation of a biological human knee. The knee must be lightweight enough to be supported by and integrated into LLEAP's linkages design. The joint must utilize some kind of actuation or powered movement that can withstand the loads generated during slow walking and sit to stand motion. The joint must also be able to be powered by a portable battery that LLEAP has chosen. Finally, the joint cannot injure the user and must be comfortable during use. Our total budget for the project is $2,000.

Aside from these required needs for the joint, the interested parties would like the actuation to be as efficient as possible to minimize power drawn from the battery. They would also like to minimize the cost as much as possible and make the design easily manufacturable. The user wants a quiet device that is preferably weather proof so it does not need to be restricted to inside use or good weather. We also want the device to require minimum maintenance during use.

The boundary diagram sketch for this design project is shown in Figure 6. The design will accept power from an external source and be connected to the thigh and shin. Within the design, we must use some kind of actuator to move the joint.

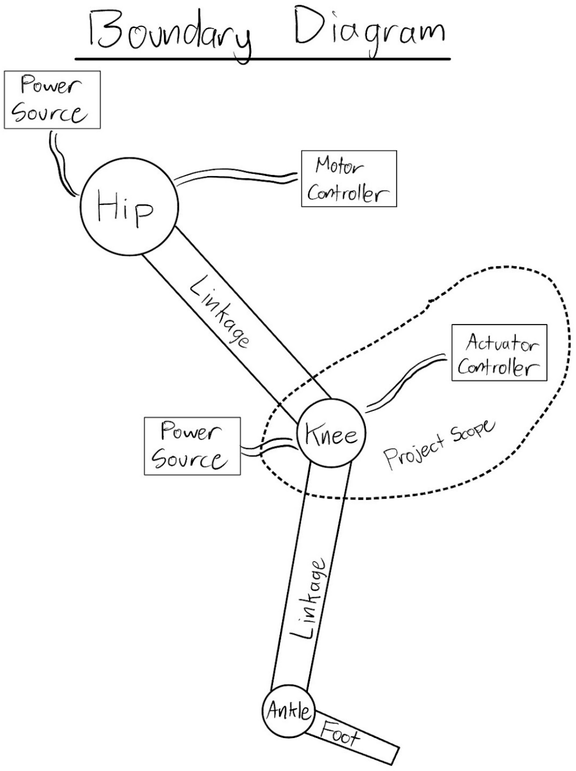

Figure 6. Boundary diagram depicting knee joint project scope.

The functional decomposition for the final product is shown in Figure 7. The overall goal is to design a knee joint for a user who is paralyzed from the chest down. Within this overarching objective, we must make the joint safe for the user, make it biomechanically accurate, design it for manufacturability, and build it to withstand expected loads. Each of these project categories have their own related components.

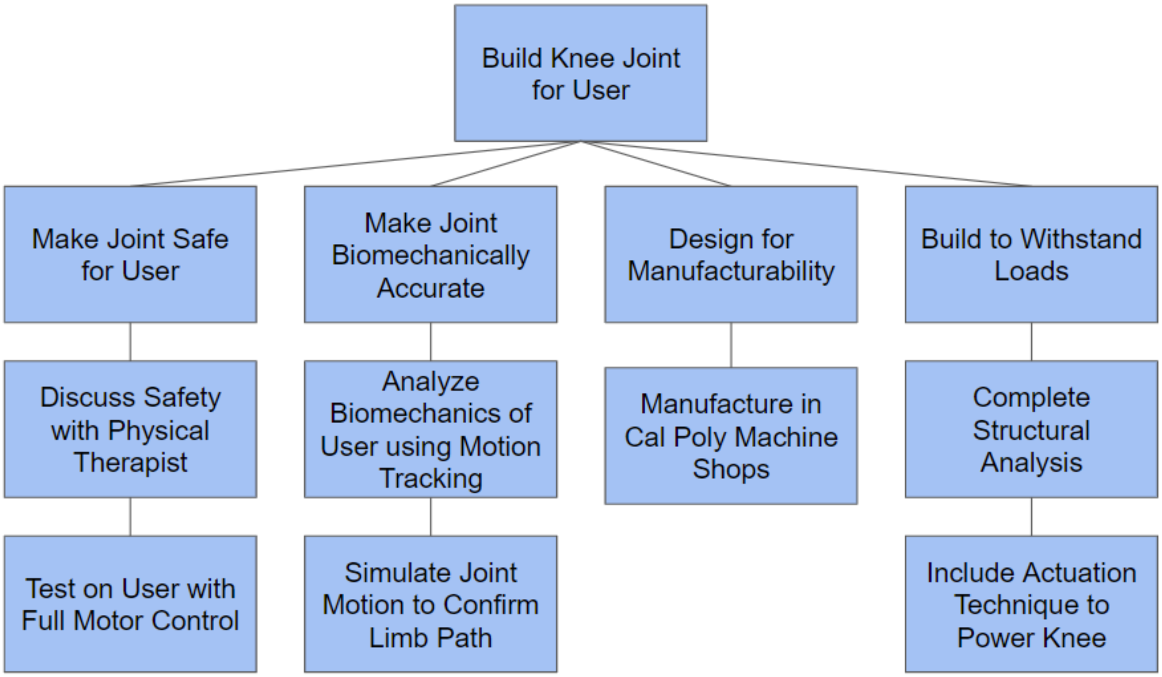

Figure 7. Function decomposition for Biomechanical Knee Joint.

By the end of this project, our team will deliver a working prototype for a biomechanically accurate knee joint. This joint will have a variable point of rotation and will include built in actuation. This actuation will be powered and controlled by an external source. The joint will include soft goods which will attach the joint to the user in a biomechanically safe and ergonomic fashion. The joint will integrate into LLEAP's 2023 prototype.

4. OBJECTIVES

Our goal is to design and fabricate a biomechanically accurate knee joint to be used by the exoskeleton being created in LLEAP for a user that is unable to walk on their own. While the specific user is not yet known, we do know their type of injury will be some form of lower-limb paralysis that inhibits them from putting weight on, or controlling their legs. Because of this, our knee joint must mimic the natural rotational movement of human knee joints, be lightweight, be safe for the user, and be actuated in a manner capable of supporting the everyday forces the user is expected to experience while using the suit to walk.

To ensure we are considering each component of this complex project, we completed a Quality Function Deployment (QFD) House of Quality for the biomechanical knee joint (Appendix B). This House of Quality lists specifications we have considered for our design, the importance of each of these specifications for each customer or user, how that specification will be tested, how each specification relates to the others, and more. We included industry exoskeletons and our club's previous design and compared their abilities to meet our listed specifications. This House of Quality will help us plan our methods for determining how well our final product achieves our goals.

The engineering specifications for the project are shown in Table 1 below. Each specification has a requirement or target value along with a tolerance, a risk rating, and a compliance label. The compliance label indicates how each specification will be tested for conformity with the requirement or target. This table summarizes one component of the House of Quality described previously in further detail.

Table 1. Engineering Specifications Table.

Spec #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Weight	<10 lbs	Max	H	A
2	Knee Kinematic Motion	3 DOFs	Target	H	I
3	Integration with Exoskeleton	Integratable	Target	L	I, S
4	Load Carrying Capability	Does not fail to dynamic loads at <1.5 mph	Min	H	A, I
5	Control of Range of Motion	Able to stop at any point in actuation	Target	L	T, A
6	User Comfort Survey	80% comfort on survey	Min	H	T
7	Fits on Test user	No slack between user and joint	Target	H	I
8	Cost	Maximum $2,000	Max	H	A
9	Range of Motion of Actuation	Full extension and flexion possible	Target	H	I, A
10	Manufacturable	Manufacturable on campus machine shops	Target	L	I
11	Comparable to knee size	Stays within 3.5in of leg (sagittal plane)	Max	H	A, I
12	Loudness	Less than 60 dB	Max	L	A, I, S
13	Waterproof	Must work after splashed with water	Target	L	T, I
14	Life of Components	100 hours of use before maintenance	Min	H	A, T
15	Fit a Variety of Users	Fits on 90% of people in group of test users	Min	H	T

*Risk of meeting specification: (H) High, (M) Medium, (L) Low

**Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

5. PROJECT MANAGEMENT

The design process for this project began with researching user needs, existing knee joint designs, knee joint biomechanics, and technical issues. Our next steps are to perform ideation and create concept models of different designs. After combining ideas and creating a singular model, we will present our preliminary design to our class and sponsor, as well as the deliverables shown in Table 2.

Table 2. Summary of project deliverables.

Milestone	Date
Scope of Work	10/18/2022
Class Preliminary Design Review	11/15/2022
Sponsor Preliminary Design Review	11/17/2022
Interim Design Review	1/24/2023
Class Critical Design Review	2/14/2023
Sponsor Critical Design Review	2/16/2023
Manufacturing and Test review	3/16/2023
Senior Project Exposition	6/2/2023
Formal Design Report Sponsor Submission	6/9/2023

Our team project plan is outlined on Team Gantt (Appendix C). All important deadlines and tasks are included on the chart. Our progress will be updated on this shared Gantt chart and specific tasks will be assigned to team members. The current chart is based on tentative dates for the next two academic quarters.

Upon completion of the scope of work, we will begin steps for our preliminary design. We will follow the ideation process, first brainstorming and defining concept models to create a preliminary design. Using pugh matrices, we will then narrow down our ideas to find the most feasible/best designs. Concept models will again be created for our top design ideas. Finally, we will create a prototype as a proof of concept. All relevant findings will be presented and discussed with our sponsor, Dr. Espinoza-Wade.

6. CONCLUSION

We are confident that we will be able to design a biomechanically accurate knee joint to be integrated into the Lower Limb Exoskeleton Assist Project’s 2023 prototype. This document outlines research that has been performed, the needs and wants of our sponsor, and the schedule we will follow to complete the project, all with the purpose of clearly stating and defining the problem proposed to our team and the work necessary to complete it. The information gathered in the document will be used to complete the ideation process and complete a preliminary design review on November 15th, 2022. Please confirm our project scope so we can successfully complete our next steps in the design process.

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8. APPENDICES

Appendix A. Research

Table 3. Biomechanics Research.

Reference Number	Document Title	Description/Use
[1]	Knee anatomy including ligaments, cartilage and meniscus	Detailed description/images of knee anatomy
[2]	Identifying the Functional Flexion-extension Axis of the Knee: An In-Vivo Kinematics Study	Detailed analysis of the axis of knee rotation with approximation
[3]	A Wearable Lower Limb Exoskeleton: Reducing the Energy Cost of Human Movement	Relevant info on joint degrees of freedom and gait analysis
[4]	Assessing effects of exoskeleton misalignment on knee joint load during swing using an instrumented leg simulator	Provides support for the need for a biomechanically accurate (non-misaligned) exoskeleton knee joint through analysis (provided).
[5]	Biomechanical Analysis of the Effects of Bilateral Hinged Knee Bracing	Specific info on the usage of a bilateral hinged joint…does not relate too much to biomechanics (though does contain calculations and an FBD of the kinetics of the knee).
[6]	NATIONAL CENTER FOR HEALTH STATISTICS Vital and Health Statistics	Anthropometric Data for the general population.
[7]	Medial Patellofemoral Reconstruction Using Quadriceps Tendon Autograft, Tibial Tubercle Osteotomy, and Sulcus-Deepening Trochleoplasty for Patellar Instability	Used as a reference for sulcus angle and reference 2.
[8]	The Axes of Rotation for the Knee	Info and data on rotation of knee joint.

Table 4. Patent Research.

Reference Number	Document Title	Description/Use
[9]	Bionic knee-ankle joint assistance exoskeleton device	Good four-bar linkage setup, but does not allow for user to sit down
[10]	Lower limb exoskeleton system having jump-down cushioning function and method thereof	Gives examples of good damping techniques for joint
[11]	Lower limb exoskeleton knee components and lower limb exoskeleton knee joint system	Gives example of adding spring stiffness to a joint
[12]	Interactive exoskeleton robotic knee system	Give info for when to lock the knee during normal gait
[13]	Semi-active robot joint	Gives info on how to use a spring to carry some forces
[14]	A kind of lower limb exoskeleton robot of four bar linkage knee joint	Has very clear four-bar linkage design that is unique
[15]	Pneumatic four-bar knee joint	Has a very compact four-bar linkage design with built in actuation
[16]	Steady ratio four-bar linkage for genuflective energy harvesting	Has detailed four-bar linkage design with curved links
[17]	Lower limb exoskeleton rehabilitation robot for children with cerebral palsy	Good design for seeing alternative knee joint actuation techniques
[18]	Assistive flexible suits, flexible suit systems, and methods for making and control thereof to assist human mobility	Has good data on forces during walking

Table 5. Technical Articles.

Reference Number	Document Title/Link	Description/Use
[19]	Exoskeleton robots for lower limb assistance: A review of materials, actuation, and manufacturing methods	Technical synthesis of materials used in a variety of exoskeletons, the manufacturing methods utilized, and various methods of actuation.
[20]	Flexible lower limb exoskeleton systems: A review	Traditionally, lower limb exoskeletons are extremely rigid. This article discusses the benefits of compliance in exoskeletons, including the frame and actuation.
[21]	Optimizing Exoskeleton Assistance for Faster Self-Selected Walking	Examination of walking speed in subjects utilizing exoskeletons with a variety of control methods and powered ankle.
[22]	Clinician-Focused Overview of Bionic Exoskeleton Use After Spinal Cord Injury	Discusses the intricacies of the effects of spinal cord injuries and the ways exoskeletons can improve symptoms and secondary conditions.
[23]	Robotic Exoskeleton Gait Training in Stroke: An Electromyography-Based Evaluation	Discusses the benefits of exoskeleton training for recovery of symmetric gait after a stroke, with a focus on the nuances of exoskeleton movement during gait.
[24]	An Anthropometrically Parameterized Assistive Lower Limb Exoskeleton	Discusses the variability in patients using exoskeletons and the importance of customizing the devices.
[25]	Assessing effects of exoskeleton misalignment on knee joint load during swing using an instrumented leg simulator	Highlights issues with strap and cuff design that causes misalignment, resulting in undesired interaction force.
[26]	Knee Joint Misalignment in Exoskeletons for the Lower Extremities: Effects on User's Gait	Uses kinematic and dynamic tests to describe effects of knee joint misalignment of users gait pattern.
[27]	Human-Exoskeleton Joint Misalignment: A Systematic Review	Outlines issues with safety and comfort of users with misalignment between the exoskeleton and the user
[28]	Physical interface dynamics alter how robotic exosuits augment human movement: implications for optimizing wearable assistive devices	Discusses how power is transmitted between wearable devices and human users.
[29]	State-of-the-art and Future Directions for Robotic Lower Limb Exoskeletons	Talks about exoskeleton power efficiency.

[30]	Review of Recent Progress in Robotic Knee Prosthesis Related Techniques: Structure, Actuation and Control	Discusses mult-axial versus axial knee prosthesis.
[31]	Analysis and performance of a semi-active prosthetic knee	Knee prosthesis with four-bar linkage, motor and screw system.
[32]	Development of prosthetic knee for alpine skiing	Four-bar linkage knee prosthetic created for above the knee amputation.

Appendix B. QFD house of quality for the biomechanical knee joint

Correlations

Positive +
Negative −
No Correlation

Relationships

Strong ●
Moderate ○
Weak ▽

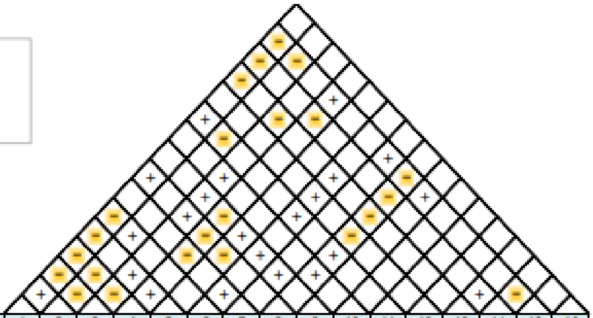
Direction of Improvement

Maximize ▲
Target ◇
Minimize ▼

QFD House of Quality

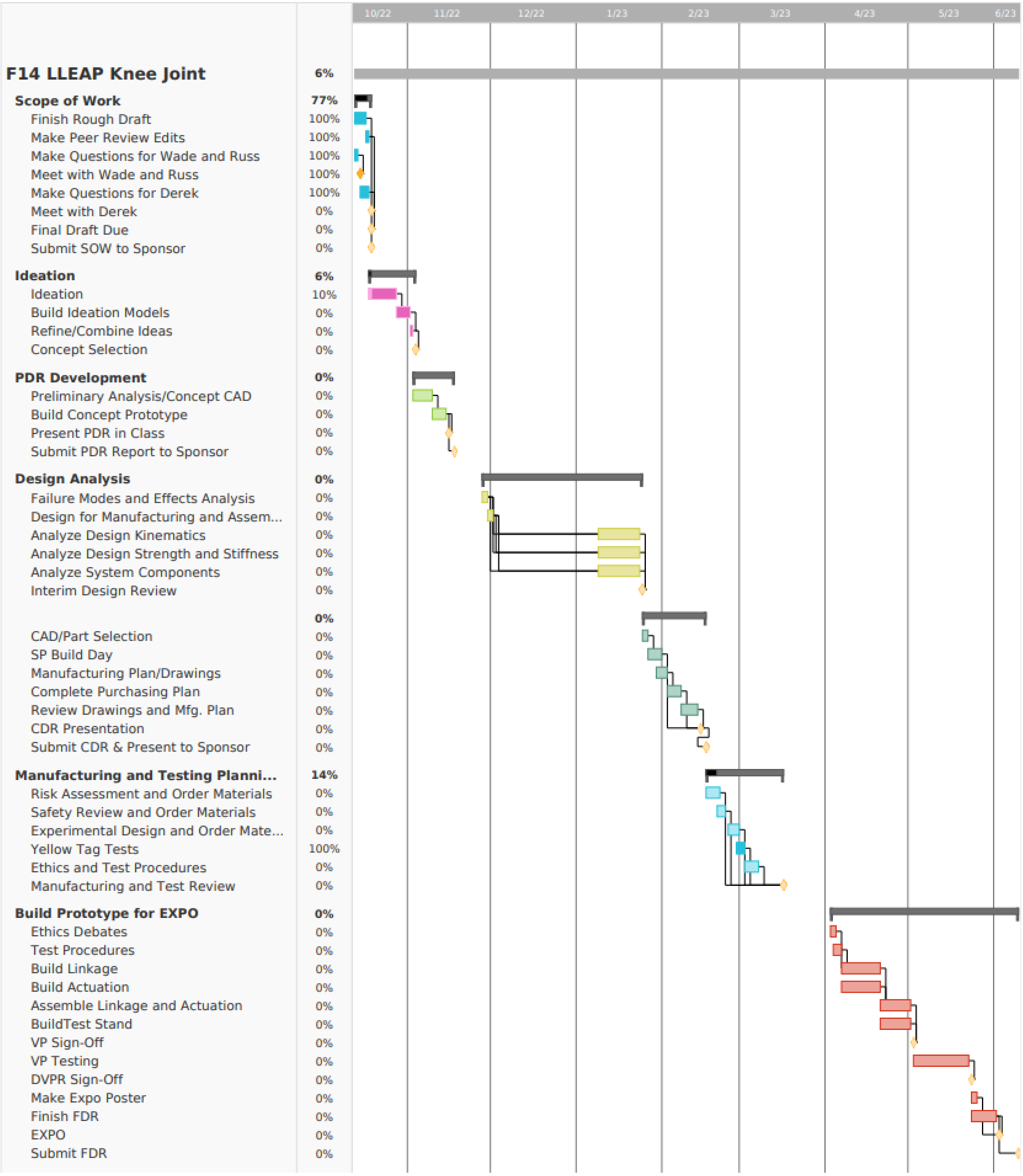
Project: Iron Man Fan Girls

Revision Date: 10/11/2022



								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers							Direction of Improvement	▼	◇	◇	▼	▲	◇	◇	▼	▲	◇	▼	▼	◇	▲	▲		NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	User	Club (LLEAP)			Maximum Relationship	HOW: Engineering Specifications (Tests) WHAT: Customer Requirements (Needs/Wants)	Weight	Knee Kinematic Motion	Integration with Exoskeleton	Point of failure	Control of Range of Motion	User comfort survey	Fits on test user	Cost	Range of motion of actuation	Manufacturable with our skills	Comparable to knee size	Loudness	Waterproof	Life of components	Fit a variety of users		Our Current Product	Competitor #1: Rewalk	Competitor #2: Exobionics	Competitor #3: Indego	Competitor #4: SuitX	Row #
1		7%	6	8			9	Lightweight	●	▽	○	○	▽			●		●	●			▽	●		3	3	4	4	5	1
2		6%	4	10			9	Biomechanically accurate		●			●	○	▽	●	●	●	○			▽	●		2	2	2	2	2	2
3		6%	3	10			9	Integratable	●	▽	●				▽	▽		▽	▽				●		1	5	5	5	5	3
4		10%	10	10			9	Supportive of Loads	○	▽	●	●	▽		▽		●		▽			●	●		5	5	5	4	5	4
5		9%	10	9			9	Safe	○	●		●	●	○	●		●					●	●		3	5	5	5	5	5
6		9%	10	8			9	Comfortable	▽	●	○			●	○		●		▽				●		1	4	3	4	5	6
7		8%	9	8			9	Testable on User	●	●	○	●	●	○	●		●		▽				●		1	5	5	5	5	7
8		4%	1	9			9	Inexpensive	▽			●				●		●			○	●	▽		4	1	1	1	1	8
9		8%	8	9			9	Effective Actuation	●	●	○		●	▽		▽	●		●			●	○		2	4	4	4	4	9
10		4%	1	9			9	Easily Manufacturable	●	●	●	●	●	○	▽	○	●	●	▽	●	●	○	▽		4	2	2	2	2	10
11		7%	7	8			9	Small	○	▽	●			▽	○	○	▽	●	●						1	4	3	3	5	11
12		5%	5	6			9	Quiet	○		●			▽		○		○		●		▽			3	4	5	4	5	12
13		3%	2	5			9	Weather Proof			▽					○		○		▽	●	●			1	1	1	1	1	13
14		8%	8	9			9	Easily Mantained			○					▽		○		▽	○	●			3	3	3	3	3	14
15		4%	2	8			9	Adjustability		○	●		○	●	●	▽	○	○				●	●		4	5	5	5	5	15
								HOW MUCH: Target Values	10 lb or lighter	3 Degrees of Freedom	Integratable	Fails due to dynamic loads at 1.5 mph	Able to stop at any point in actuation	80% comfort on survey	No slack between user and joint	Maximum $2000.00	Full extension and flexion possible	Manufacturable on Campus	Stay within 1.5in of leg (sagittal plane)	Less than 60 dB	Must work after exposer to water	100 hrs of use before maintainance	Fits on all people in group of test users							
								Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9							
								Technical Importance Rating	406.7	451.5	453.3	342.9	357.6	225.4	273.8	240	517.3	325.3	255.1	96.34	102.8	456	569.1	0						
								Relative Weight	8%	9%	9%	7%	7%	4%	5%	5%	10%	6%	5%	2%	2%	9%	11%	0%						
							Curr. Products	Our Current Product	1	1	3	5	5	3	2	5	5	4	1	4	1	5	1							
								Competitor #1: Rewalk	3	1	5	5	5	3	5	1	5	1	4	4	1	3	5							
								Competitor #2: Exobionics	4	1	4	5	5	4	5	1	5	1	3	4	1	3	5							
								Competitor #3: Indego	4	1	5	5	5	2	4	1	5	1	3	4	1	3	5							
								Competitor #4: SuitX	5	1	2	5	5	2	5	1	5	1	5	4	1	3	5							
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						

Appendix C. Gantt chart for project



F14 LLEAP Knee Joint	**6%**
Scope of Work	**77%**
Finish Rough Draft	100%
Make Peer Review Edits	100%
Make Questions for Wade and Russ	100%
Meet with Wade and Russ	100%
Make Questions for Derek	100%
Meet with Derek	0%
Final Draft Due	0%
Submit SOW to Sponsor	0%
Ideation	**6%**
Ideation	10%
Build Ideation Models	0%
Refine/Combine Ideas	0%
Concept Selection	0%
PDR Development	**0%**
Preliminary Analysis/Concept CAD	0%
Build Concept Prototype	0%
Present PDR in Class	0%
Submit PDR Report to Sponsor	0%
Design Analysis	**0%**
Failure Modes and Effects Analysis	0%
Design for Manufacturing and Assem...	0%
Analyze Design Kinematics	0%
Analyze Design Strength and Stiffness	0%
Analyze System Components	0%
Interim Design Review	0%
	0%
CAD/Part Selection	0%
SP Build Day	0%
Manufacturing Plan/Drawings	0%
Complete Purchasing Plan	0%
Review Drawings and Mfg. Plan	0%
CDR Presentation	0%
Submit CDR & Present to Sponsor	0%
Manufacturing and Testing Planni...	**14%**
Risk Assessment and Order Materials	0%
Safety Review and Order Materials	0%
Experimental Design and Order Mate...	0%
Yellow Tag Tests	100%
Ethics and Test Procedures	0%
Manufacturing and Test Review	0%
Build Prototype for EXPO	**0%**
Ethics Debates	0%
Test Procedures	0%
Build Linkage	0%
Build Actuation	0%
Assemble Linkage and Actuation	0%
BuildTest Stand	0%
VP Sign-Off	0%
VP Testing	0%
DVPR Sign-Off	0%
Make Expo Poster	0%
Finish FDR	0%
EXPO	0%
Submit FDR	0%